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MARKED INFLUENCE OF CRYSTAL STRUCTURE  
ON THE FRICTION AND WEAR CHARACTERISTICS  
OF COBALT AND COBALT-BASE ALLOYS  
IN VACUUM TO  $10^{-9}$  MILLIMETER OF MERCURY  
I — POLYCRYSTALLINE AND SINGLE  
CRYSTAL COBALT

*by Donald H. Buckley and Robert L. Johnson*

*Lewis Research Center*

*Cleveland, Ohio*



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SUMMARY

Friction and wear characteristics were determined for polycrystalline cobalt sliding on various materials (polycrystalline cobalt, 440-C, 52100, and aluminum oxide) in vacuum ( $10^{-9}$  mm Hg). The influence of crystal transformation on the friction and wear characteristics of cobalt were determined by varying sliding velocity and ambient temperature. The effect of orientation of single-crystal cobalt sliding on polycrystalline cobalt was also determined. Friction and wear experiments were conducted at sliding velocities to 2000 feet per minute and ambient temperatures to  $850^{\circ}$  F. Both polycrystalline and oriented single crystals of cobalt were the rider specimens ( $3/16$ -in.-rad. hemisphere) sliding on flat  $2\frac{1}{2}$ -inch-diameter disks of various materials. Factors studied were the influences of crystal transformation and single crystal orientation on the friction and wear characteristics of cobalt.

The results of the investigation indicate that crystal transformation in cobalt markedly influences friction and wear characteristics in vacuum. The hexagonal crystal form of cobalt exhibited much lower friction and wear characteristics than the face-centered-cubic form. With single crystals of cobalt, orientation influenced friction properties. The friction coefficient in vacuum was less for the 0001 plane oriented parallel to the direction of sliding than for the 1100 plane oriented parallel to the direction of sliding.

INTRODUCTION

The selection of materials for use in space lubrication systems requires a careful consideration of both lubricants and metals, or alloys, used as the mechanical components of these systems. The lack of oxygen encountered at the low ambient pressures of the environment of space can result in high friction, metal transfer, and complete welding of metal components in contact should failure (by evaporation, decomposition, or wearing away) of the lubricant occur.

One approach to obtaining alloys with good friction and wear characteristics is that of incorporating lubricating microconstituents directly into conventional alloy structures (refs. 1 to 5). Also of interest is examination of the influence of elemental properties of metals such as crystal structure and phases on their friction and wear characteristics in vacuum. For example, it is demonstrated in reference 6 that with rare earth and related metals which undergo crystal transformations the hexagonal crystal forms of these metals exhibit much better friction and wear characteristics and less metal transfer than cubic forms of the same metals.

Cobalt and cobalt-containing alloys have been shown to have good friction and wear characteristics (ref. 7) and have been examined for bearing (ref. 8) and seal applications (ref. 9). Cobalt at room temperature exists in a hexagonal close-packed form and transforms to a face-centered-cubic structure at 734° to 800° F (refs. 10 to 19). Cobalt tends to exist, however, as a mixture of two allotropes over a wide range of temperatures with the hexagonal form predominating below the transformation temperature and the face-centered-cubic form above that temperature. The transformation is sluggish, which probably accounts for the wide variations in data reported for its physical properties (ref. 10). Because of the desirable friction and wear characteristics obtained with the hexagonal forms of some metals in reference 3, it was decided to examine the friction and wear characteristics of cobalt in vacuum. In a vacuum the influence of surface contaminants, such as oxides and adsorbed gases, is appreciably reduced and, therefore, a more critical evaluation of the role of crystal structure on friction and wear properties can be gained.

This investigation was therefore conducted to determine in vacuum (1) the effect of the crystal structure of cobalt on its friction, wear, and metal-transfer characteristics; and (2) the effect of single crystal orientation on these properties.

#### APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown in figure 1. The basic elements of the apparatus were the specimens (a  $2\frac{1}{2}$ -in.-diam. flat disk and a  $3/16$ -in.-rad. rider) mounted in a vacuum chamber. The disk specimen was driven through a magnetic drive coupling. The coupling had two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The driver magnet that was outside the vacuum system was coupled to a hydraulic motor. The second magnet was completely covered with a nickel-alloy housing and was mounted on one end of the shaft within the chamber (fig. 1). The end of the shaft that was opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm that was mounted by gimbals and bellows to the chamber. A linkage at the end of the retaining arm, away from the rider specimen, was connected to a strain-gage assembly. The assembly was used to measure frictional force. Load was applied through a dead-weight loading system.

Attached to the lower end of the specimen chamber was a 400-liter-per-

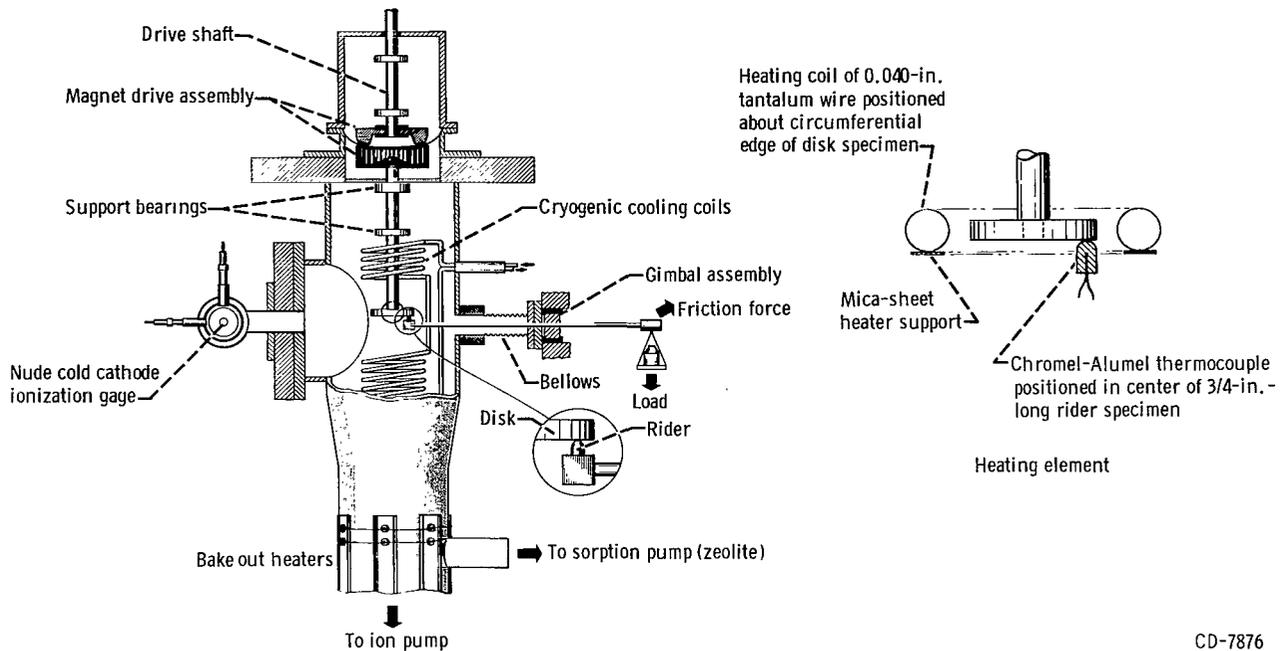


Figure 1. - High-vacuum friction and wear apparatus.

second ionization pump and a mechanical forepump with liquid-nitrogen cold traps. The pressure in the chamber was measured adjacent to the specimen with a cold cathode ionization gage. In the same plane as the specimens and ionization gage was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases present in the vacuum system. A 20-foot-long stainless-steel coil of 3/16-inch-diameter tubing was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

In experiments where external heating of the specimens was required, a wire-wound tantalum heater was placed adjacent to the circumferential edge of the disk specimen (fig. 1). A thermocouple was inserted in the rider and the bulk specimen temperature recorded. No attempt was made to record interface temperatures.

### Specimen Preparation

The polycrystalline cobalt used in this investigation was prepared from electrolytic cobalt. Electrolytic cobalt chips were packed into a zirconium oxide crucible and placed into an induction vacuum furnace, which was then evacuated. The furnace was then back-filled with dry argon, and the cobalt was raised to a temperature of 2800° F. The cobalt was then poured into a copper mold and cooled to room temperature. The chemical analysis of the resulting casting is presented in table I. The nickel and the iron specimens used in this investigation were prepared in a similar manner. After they were machined to required dimensions and surface finishing, the cobalt specimens were heat-treated for 4 hours at 700° F to minimize the concentration of face-centered form. This particular heat treatment was employed because, as stated in

TABLE I. - COMPOSITION OF COBALT USED

IN FRICTION AND WEAR STUDIES

Element	Percent
Oxygen	0.026
Zirconium	.02
Nickel	.02
Iron	.01
Copper	.03
Carbon	.0094

reference 17, the amount of face-centered-cubic structure that may be present at room temperature can vary from 5 to 30 volume percent depending upon the thermal history of the material.

Specimen Finish and Cleaning Procedure

The disk and the rider specimens used in friction and wear experiments were finished to a roughness of 4 to 8 microinches. Before each experiment, the disk and the rider were given the same preparatory treatment:

- (1) A thorough rinsing with acetone to remove oil and grease
- (2) A polishing with moist levigated alumina on a soft polishing cloth
- (3) A thorough rinsing with tap water followed by distilled water

For each experiment, a new set of specimens was used.

RESULTS AND DISCUSSION

Cobalt Sliding on Cobalt

Friction and wear experiments were conducted with recast and heat-treated cobalt. Hereinafter these specimens will be referred to as cobalt. Some friction experiments were conducted in vacuum with cobalt sliding on cobalt. Experiments were conducted to determine friction characteristics both as a function of sliding velocity and of ambient temperature. The results obtained in these experiments are presented in figures 2 and 3. In figure 2 an increase in sliding velocity resulted in an increase in friction coefficient at 1500 feet per minute. The increase in coefficient of friction at this sliding velocity is believed to be due to the transformation of cobalt from the hexagonal crystal form to the face-centered cubic structure. The transformation, however, is believed to reflect a transformation of only the rider specimen from the hexagonal to the cubic form. In these friction studies the rider specimen is in continuous sliding contact and represents only one-twentieth of the mass of the disk specimen; consequently, it experiences much higher bulk temperatures

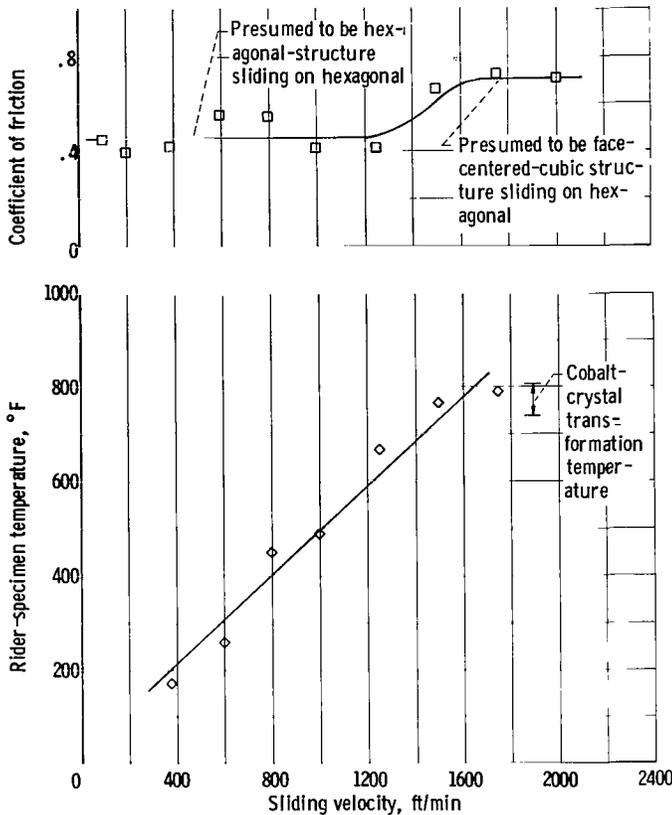


Figure 2. - Coefficient of friction and rider specimen temperatures at various sliding velocities for cobalt sliding on cobalt in vacuum ( $10^{-9}$  mm Hg). Load, 1000 grams.

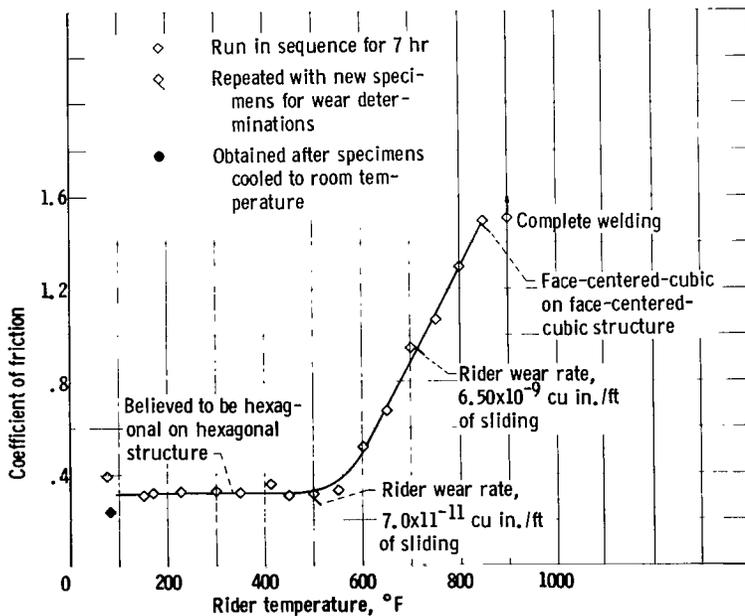


Figure 3. - Coefficient of friction at various ambient temperatures for cobalt sliding on cobalt in vacuum ( $10^{-8}$  to  $10^{-7}$  mm Hg). Load, 1000 grams; sliding velocity, 390 feet per minute.

than the disk specimen, which is in intermittent contact. At sliding velocities below 1200 feet per minute, a predominantly hexagonal crystal form is sliding on a predominantly hexagonal crystal form. At sliding velocities in excess of 1500 feet per minute, a predominantly face-centered-cubic structure is sliding on a predominantly hexagonal crystal form. Bulk rider-specimen temperatures measured during the experiment were  $670^{\circ}$  F at 1250 feet per minute and  $770^{\circ}$  F at 1500 feet per minute (fig. 2). At the higher sliding velocity, the temperature of the rider was in the region associated with the crystal transformation (refs. 10 to 12) from hexagonal to face-centered-cubic cobalt.

Friction data obtained for cobalt sliding on cobalt at various ambient temperatures are presented in figure 3. The coefficient of friction for cobalt sliding on cobalt was approximately 0.3 at ambient temperatures to  $550^{\circ}$  F in vacuum. Above  $550^{\circ}$  F, the friction coefficient began to increase very rapidly. At an ambient temperature of  $850^{\circ}$  F (above the temperature for crystal transformation), a friction coefficient of 1.5 was recorded; subsequently, complete welding of the disk and the rider specimen occurred. At temperatures below  $550^{\circ}$  F, the hexagonal crystal form of cobalt is sliding on the hexagonal crystal form of cobalt. Above  $550^{\circ}$  F, the influence of the transformation is observed; above  $850^{\circ}$  F, face-centered-cubic cobalt is sliding on face-centered-cubic cobalt.

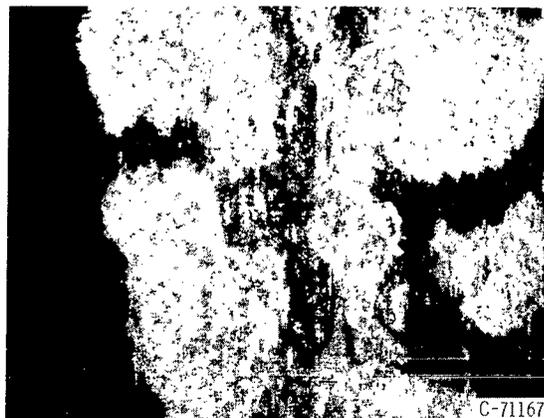
It is of interest to note that in sliding velocity experiments where only one of the specimens (the rider) transformed from the hexagonal to the face-centered-cubic structure, the maximum friction coefficient obtained was 0.7. In the increasing temperature experiments, however, where the temperature of both specimens reached the transformation temperature, the friction coefficient was 1.5 with complete welding occurring. With cobalt sliding on cobalt, the results of these experiments indicate that (1) the lowest coefficient of friction is obtained with the hexagonal crystal form sliding on the hexagonal crystal form, (2) intermediate values are obtained with the face-centered-cubic form sliding on hexagonal form, and (3) the maximum friction coefficients are obtained with complete welding for the face-centered-cubic structure sliding on the face-centered-cubic form.

The crystal transformation for cobalt is reversible as indicated in references 10 and 16 to 18. This reversible nature of the transformation is reflected in the friction data point shown in figure 3 at 75° F after the specimens were cooled slowly in vacuum from 850° F.

Separate wear experiments were conducted at two ambient temperatures (500° and 700° F) with cobalt sliding on cobalt in order to determine the influence of the transformation on wear. The rider wear values obtained at these two temperatures are also presented in figure 3; photomicrographs and surface-profile traces of the disk surfaces are presented in figure 4. The rider wear rate at 500° F was  $7.0 \times 10^{-11}$  cubic inch per foot of sliding as compared with  $6.50 \times 10^{-9}$  cubic inch per foot of sliding at 700° F, or difference in wear of 100. Wear was measured at 700° F rather than at 850° F because of the complete welding obtained at 850° F.



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(a) Temperature, 500° F; measured rider wear rate,  $7.0 \times 10^{-11}$  cubic inch per foot of sliding.

(b) Temperature, 700° F; measured rider wear rate,  $6.50 \times 10^{-9}$  cubic inch per foot of sliding.

Figure 4. - Photomicrographs and surface profile traces of disks of cobalt sliding on cobalt in vacuum ( $10^{-9}$  mm Hg) at two rider temperatures. Load, 1000 grams; sliding velocity, 390 feet per minute; run duration, 1 hour.

It is very important to note that the point in both the sliding-velocity and ambient-temperature curves at which friction begins to increase is below the actual transformation temperature. This effect is believed to result because the temperature near the interface and at the position of the thermocouple in the rider differ. With very careful positioning of thermocouples, it may be possible to determine accurately crystal transformation temperatures from friction data.

In the photomicrograph of figure 4(a), metal appears to have been transferred to the disk surface. This occurrence is, however, merely plastic flow, as distinguished from metal transfer as observed in both the photomicrographs and the surface profile trace of figure 4(b).

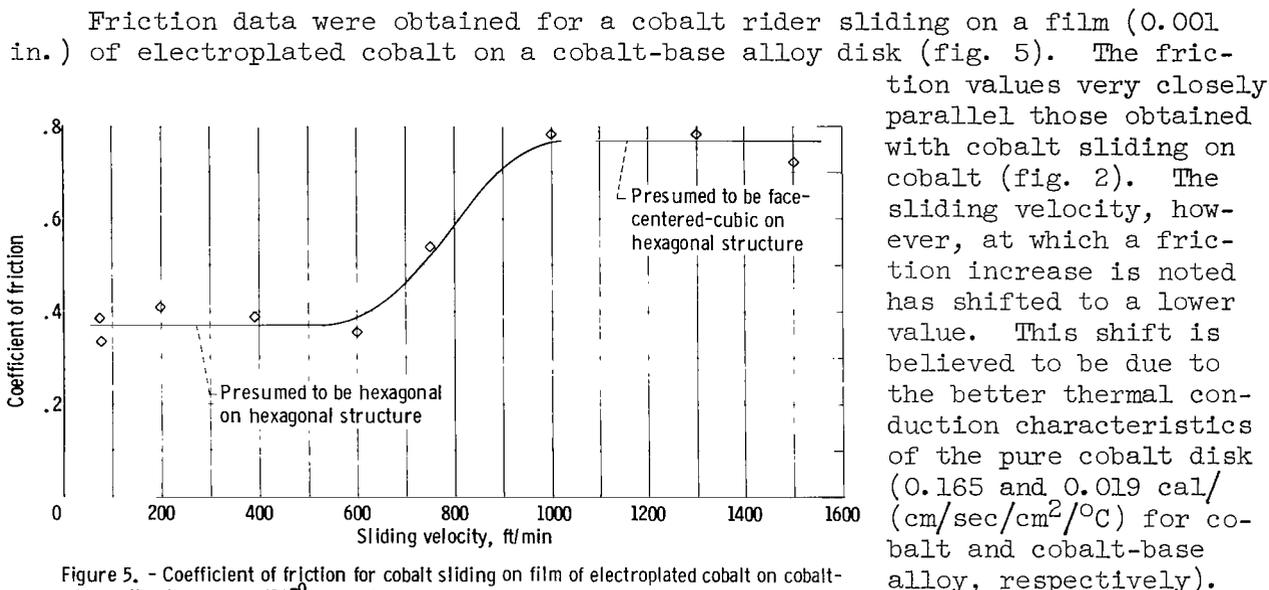


Figure 5. - Coefficient of friction for cobalt sliding on film of electroplated cobalt on cobalt-base alloy in vacuum (10<sup>-9</sup> mm Hg). Load, 1000 grams; no external specimen heating.

#### Cobalt Sliding on 440-C Stainless Steel

In order to determine the influence of the crystal transformation of cobalt on friction coefficient when cobalt is sliding on surfaces other than cobalt, some friction and wear experiments were conducted with electrolytic cobalt sliding on 440-C stainless steel in vacuum. The results obtained in some of these experiments are presented in figure 6. With cobalt sliding on 440-C at low sliding velocities, a hexagonal crystalline material is sliding on a body-centered-cubic structure. Examination of the friction data of figure 6, however, indicates a friction coefficient of 0.3 to 0.4, the same value obtained in figures 2, 3, and 5 with hexagonal cobalt sliding on hexagonal cobalt. Chemical analysis of the disk surface upon completion of such experiments revealed the presence of a transfer film of cobalt on the 440-C disk. The friction data then at sliding velocities below 500 feet per minute reflect hexagonal cobalt sliding on a thin film of cobalt. At sliding velocities in excess of 500 feet per minute, the crystal transformation of cobalt occurs; ultimately, face-centered-cubic cobalt sliding on body-centered-cubic 440-C at 1000 feet per minute is obtained. The cobalt transfer film (fig. 7(a)) may not

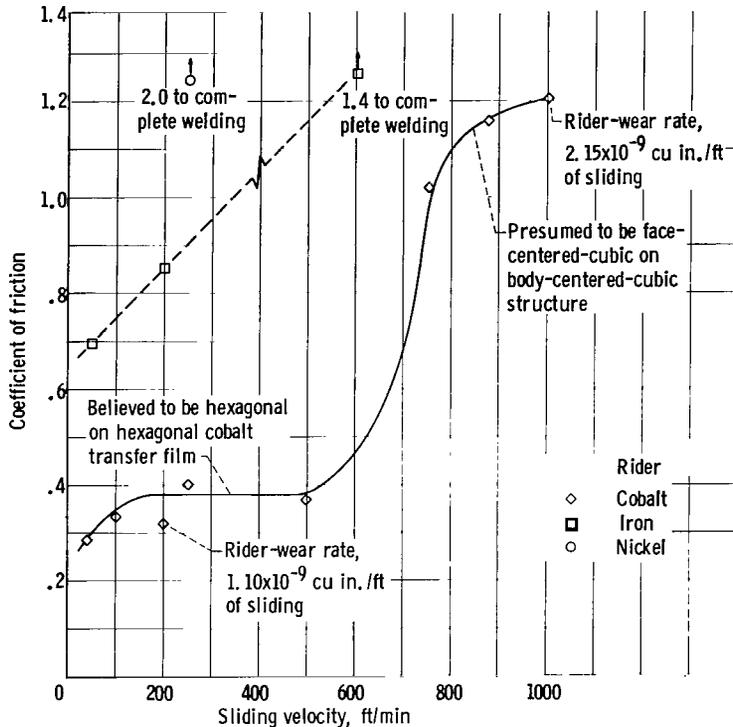


Figure 6. - Coefficient of friction for cobalt, iron, and nickel sliding on 440-C stainless steel in vacuum ( $10^{-9}$  mm Hg) at various sliding velocities. Load, 1000 grams; no external specimen heating.

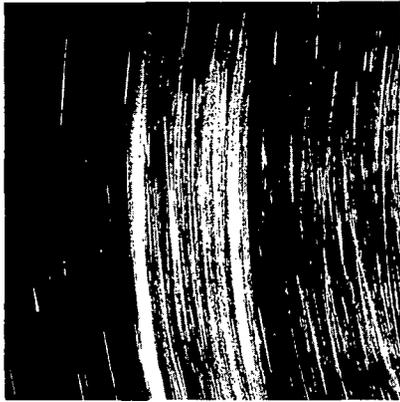
wear value. Photomicrographs of the disk wear areas together with surface profile traces for the 440-C disk surfaces are presented in figure 7. The presence of cobalt mass-transferred to the 440-C surface at 1000 feet per minute is indicated by the surface profile trace of figure 7(b); the thin film transfer is indicated by figure 7(a).

For comparison, friction data were also obtained for two metals with cubic structures (iron and nickel) sliding on 440-C. The results obtained with these two metals are also presented in figure 6. With iron (99.9 percent) sliding on 440-C the initial coefficient of friction of 0.7 increased to 1.4, at which time complete welding of the iron with the 440-C disk occurred. The experiment with nickel (99.9 percent) was started at a higher sliding velocity because of the extreme difficulty encountered at lower speeds in obtaining representative friction values. At 250 feet per minute, however, a friction coefficient of 2.0 was measured, shortly after which complete welding of the rider and the disk occurred. When the specimens welded, the magnetic drive of the apparatus began slipping. These results indicate that the close-packed hexagonal metal cobalt has superior friction properties in vacuum when sliding on 440-C as compared with the cubic metals nickel and iron.

In order to obtain some knowledge of what influence surface temperatures have on the structures of the friction specimens used in this investigation, the iron and cobalt rider specimens that slid against 440-C disks were sectioned through the center and mounted and photomicrographs of the interface

retain its continuity upon transformation of crystal structure in the rider specimen. With thicker cobalt films, as in figure 5, this lack of continuity is not observed.

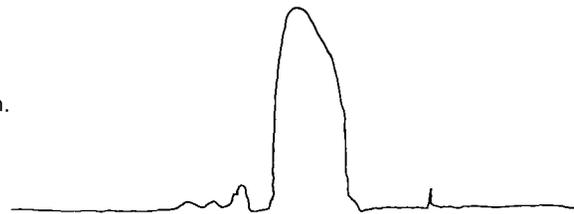
Rider-wear rates were measured at two sliding velocities, 200 and 1000 feet per minute, in an attempt to determine the influence of crystal transformation on wear. As indicated in figure 6, the rider wear rate at 1000 feet per minute was nearly twice that obtained at 200 feet per minute. Although the wear rate at the high velocity is not as large as anticipated, appreciable metal transfer occurred at 1000 feet per minute with a continuous back-and-forth transfer of metal from rider to disk surface, which is not reflected in the



← 0.05 in. →



↑  
0.005 in.  
↓



(a) Sliding velocity, 200 feet per minute.

(b) Sliding velocity, 1000 feet per minute.

Figure 7. - Photomicrographs and surface profile traces of 440-C stainless steel disk wear surfaces. Rider specimen, cobalt; load, 1000 grams; temperature, 75° F; run duration, 1 hour.

region were taken. Photomicrographs of the iron and cobalt riders are shown in figures 8 and 9. In figure 8 a large amount of plastic flow appears to have occurred in the sliding process, as evidenced by the streamers of metal projecting from the trailing edge of the rider specimen (photomicrograph A). When the interface region was sectioned and etched, the grain boundaries of the bulk rider specimen appeared (photomicrographs B and C). In the immediate interface area and in the trailing metal streamers, an "amorphous-type" structure is evidenced. If the area immediately adjacent to the sliding interface is examined under higher magnification (photomicrograph D), the iron structures appear to change to an amorphous state. A similar type structure is observed for the cobalt-rider specimen in figure 9.

The presence of a region at the interface where grains are reduced to small crystallites or to an amorphous state is extremely interesting. The Beilby concept of an amorphous film generated during the polishing process has in recent years been put aside in favor of a theory of extremely small crystallite size beyond the detection of even electron diffraction. More recent work, however, with metastable structure seems to substantiate the existence of such a film. The individual crystals in a polycrystalline material may range in size from macroscopic dimensions down to the unit of structure. It is then somewhat obvious that there can be no regular repetition in the atomic pattern

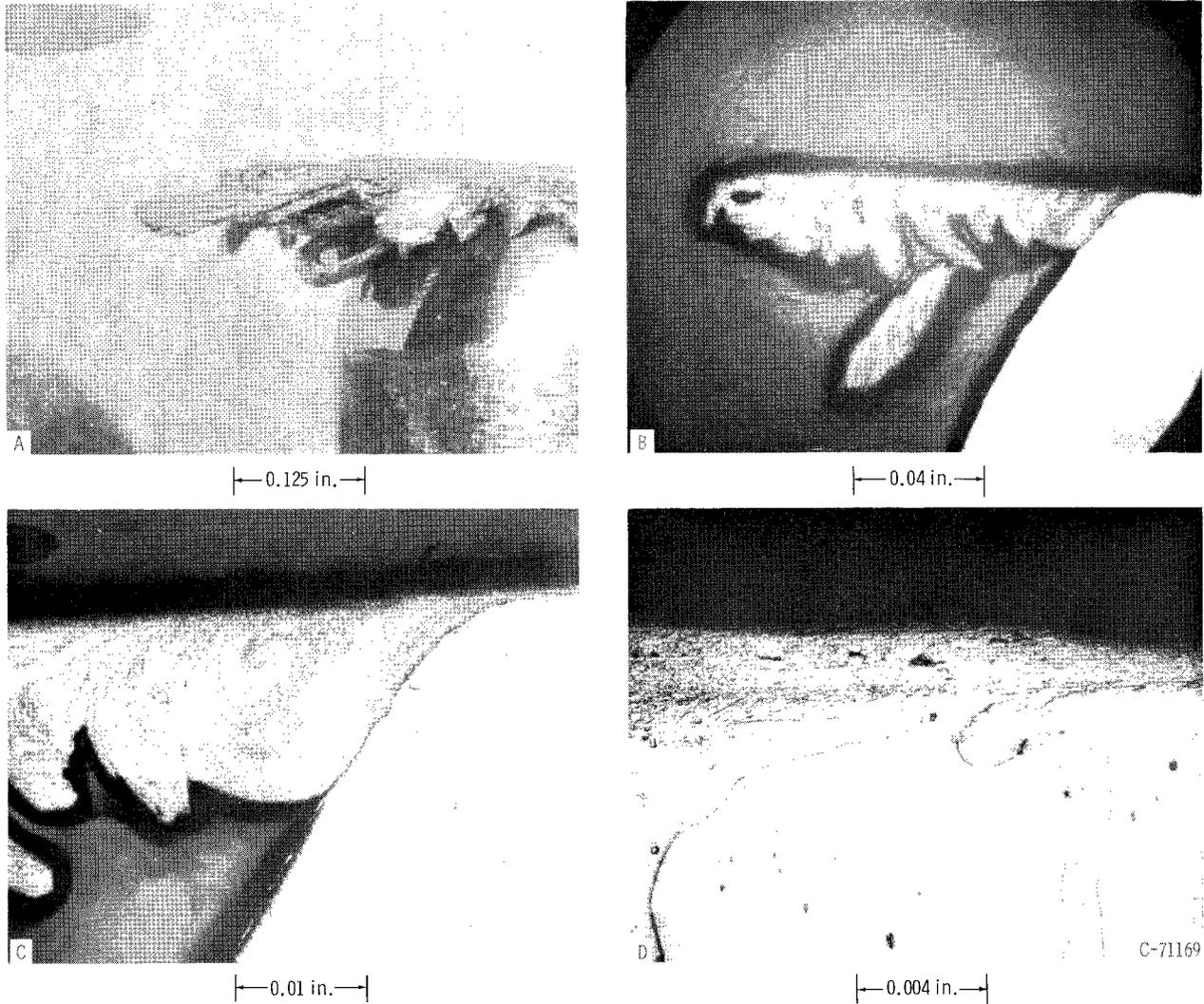


Figure 8. - Photomicrographs of high-purity iron rider specimen.

if the crystallite size is of the order of one structural unit, and the crystallinity would really be zero at the lower limit of crystallite size. If this is true, the amorphous, or Beilby layer, concept and that of small crystallite size are for all practical purposes the same.

In order to determine whether the structure generated in the process of sliding in figure 8 was crystalline or amorphous, an X-ray diffraction pattern was taken of this region. The X-ray pattern revealed that the material which appears to lack distinct grain boundaries was in fact crystalline.

#### Cobalt Sliding on 52100 Alloy

An alloy frequently used in the bearing industry is 52100. In order to gain some insight into the transformation behavior of cobalt sliding on an alloy other than 440-C, some friction experiments were conducted for cobalt

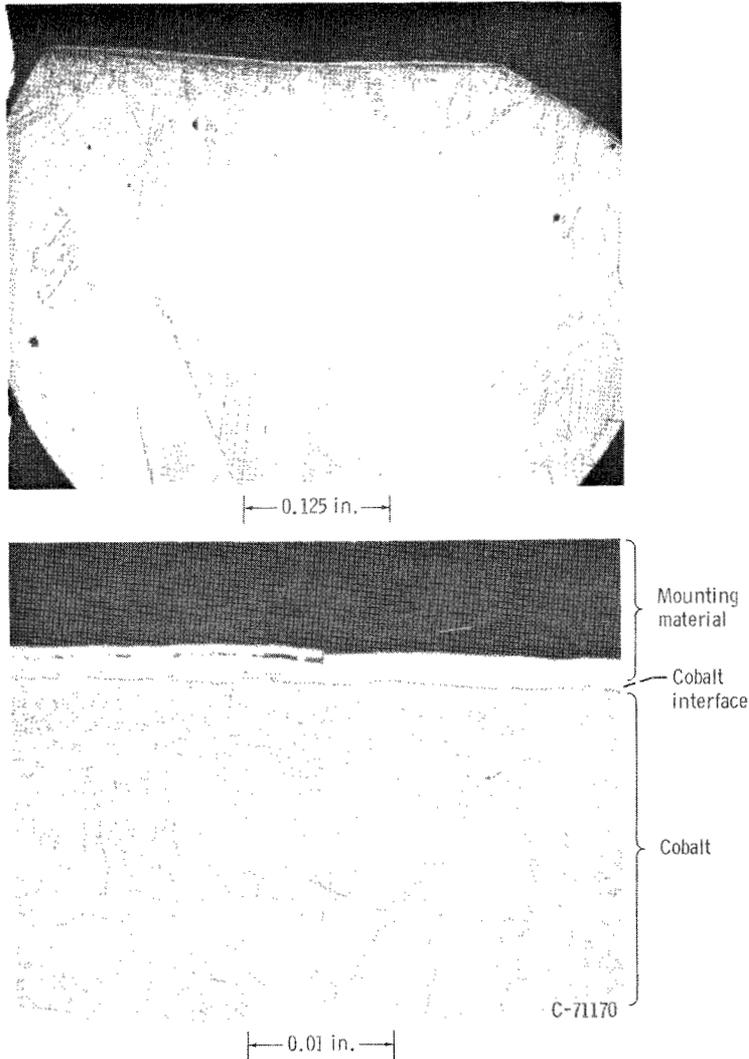


Figure 9. - Photomicrographs of cobalt rider specimen at sliding interface region.

sliding on 52100 at various sliding velocities. The results obtained in these experiments are presented in figure 10. The friction experiments were conducted both in air at 760 millimeters of mercury and in vacuum ( $10^{-9}$  mm Hg). In vacuum, the friction coefficient for cobalt sliding on 52100 at sliding velocities of 600 feet per minute and less was approximately 0.2. Chemical tests of the surface of the 52100 disk upon completion of the friction experiment revealed the presence of a cobalt transfer film on 52100. Just, as was experienced with 440-C, the sliding pair is essentially cobalt in its hexagonal form sliding on a thin cobalt transfer film. At a sliding velocity of 800 feet per minute, the friction coefficient increased to 0.95 with the assumed crystal transformation of cobalt to the face-centered-cubic form. The transformation is gradual as indicated in figure 11. With 440-C disk surfaces, the change was more rapid. The reason for the downward trend (fig. 10) at sliding velocities in excess of 1000 feet per minute is not fully understood.

It is interesting to note in the sliding velocity experiments in vacuum that the thermal conductivity of the disk material seems to influence the rider specimens transformation. With cobalt sliding on cobalt, the friction increased at sliding velocities in excess of 1250 feet per minute. The 52100 and 440-C disk materials are poorer conductors than pure cobalt (thermal conductivity: cobalt, 0.165; 52100, 0.093; and 440-C, 0.048 cal/(cm<sup>2</sup>/cm/°C/sec)), and the transformation therefore occurs at lower sliding velocities (approximately 600 ft/min) because of the higher interface temperature.

In order to determine if the crystal transformation of cobalt influenced the friction coefficient when transfer surface films previously formed in vacuum were present, friction data were obtained for cobalt sliding on 52100 in dry air (fig. 10(a)). The coefficient of friction decreases with increasing sliding

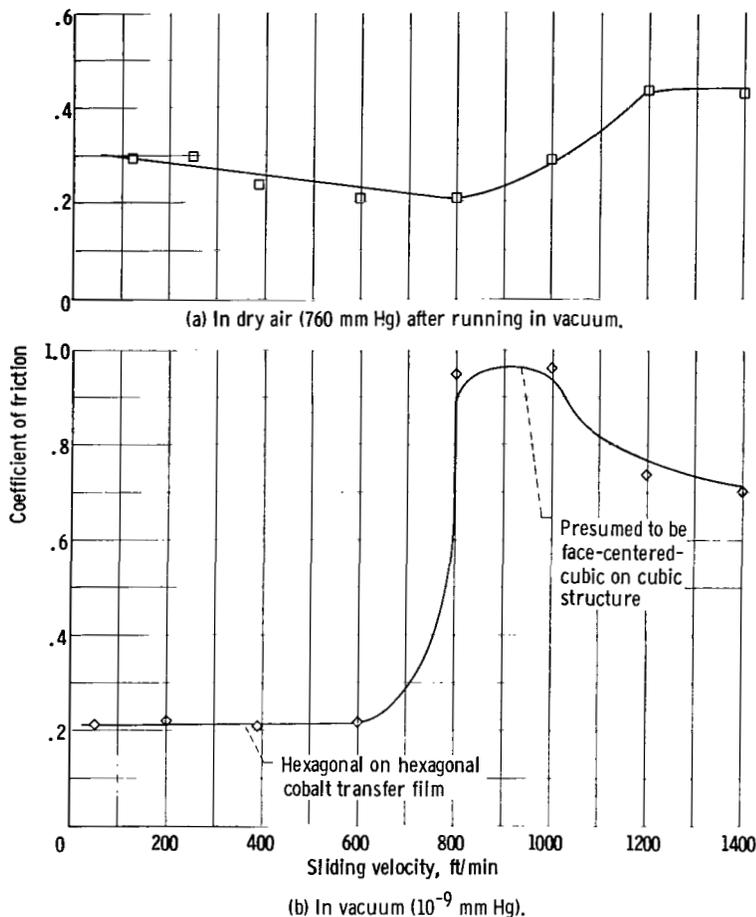


Figure 10. - Coefficient of friction for cobalt sliding on 52100 at various sliding velocities in air and in vacuum ( $10^{-9}$  mm Hg). Load, 1000 grams; no external specimen heating.

velocity. An increase in friction is observed in the same region of sliding velocity as noted in the vacuum experiment. It is very interesting to compare the friction data obtained in air with cobalt sliding on 52100 with those of reference 7 for cobalt sliding on cobalt at various ambient temperatures in air. These data of reference 7 are similar to those obtained in this investigation. It must be indicated that the friction data obtained in the present investigation were obtained with specimens that had been previously run in vacuum to allow for a transfer film of cobalt to form on the 52100. In reference 7 varying the ambient temperature seems to have produced the same effect observed in this investigation by varying sliding velocity. Although the changes in friction properties in air are not marked, they do indicate the transformation of cobalt.

#### Cobalt Sliding on Aluminum Oxide

Since during the sliding of a metal on a metal in the absence of surface oxides strong adhesion between the two metal surfaces can occur, it was decided to examine cobalt in sliding contact with a nonmetal (aluminum oxide) to ascertain the influence of a nonmetal on the crystal transformation of cobalt. Friction data were obtained with a cobalt rider sliding on a solid aluminum oxide disk in vacuum (fig. 12). These data did not reflect the crystal transformation of cobalt. Aluminum oxide has a thermal conductivity of 0.00613 (cal/( $\text{cm}^2/\text{cm}/^\circ\text{C}/\text{sec}$ )) as compared with 0.093 and 0.048 (cal/( $\text{cm}^2/\text{cm}/^\circ\text{C}/\text{sec}$ )) for 52100 and 440-C, respectively. Since thermal conductivity of the disk surface exerts an influence on the sliding velocity at which transformation is observed, a change in friction should have been observed with aluminum oxide at a sliding velocity lower than that at which it occurred with 52100 and 440-C.

With metals sliding on metals, the strong bonds of adhesion associated with metal structures can develop. In aluminum oxide, which is thermodynamically stable, however, the aluminum metallic ion is surrounded by oxygen ions, and, as a result, the aluminum ions do not have an opportunity to form strong

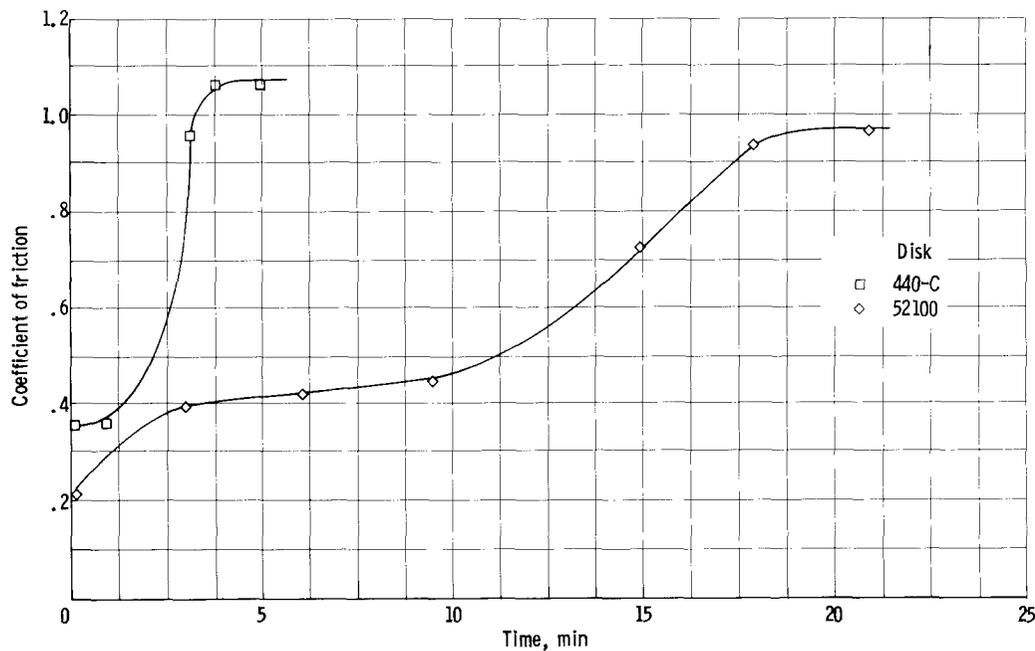


Figure 11. - Coefficient of friction as function of time for cobalt sliding on 52100 and 440-C. Sliding velocity, 800 feet per minute; load, 1000 grams; no external specimen heating.

metal-to-metal bonds of adhesion with cobalt because they do not come into intimate contact. Thus, factors such as crystal structure, which may affect these bonds, have no influence with cobalt sliding on aluminum oxide; hence, a change in friction with sliding velocity would not be expected to occur even though a transformation occurs.

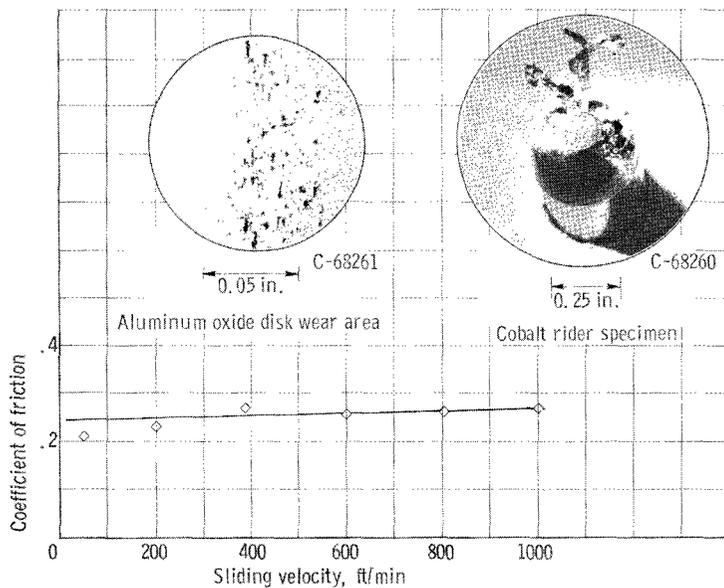


Figure 12. - Coefficient of friction for cobalt rider sliding on aluminum oxide disk in vacuum ( $10^{-9}$  mm Hg). Load, 1000 grams; no external specimen heating.

It is interesting to note the wear area of the aluminum oxide disk and the rider specimen in the photographs of figure 12. Examination of the disk specimen wear area revealed the presence of some transferred cobalt believed to be the result of mechanical transfer. The cobalt rider specimen has large streamers of metal attached that formed during the course of sliding. These streamers, when examined microscopically at high magnifications, were revealed to have resulted from plastic flow of metal. They were not composed of discrete particles.

## Oriented Cobalt Single Crystals

It has been demonstrated in the literature (refs. 20 and 21) that various crystal surfaces of copper exhibit differences in friction characteristics. If such differences exist for a cubic metal like copper, they must also exist for hexagonal metals such as cobalt. For hexagonal metals in which there are strong tendencies for orientation, knowledge of the function characteristics of various planes would be helpful.

Since crystal structure influences the friction characteristics of cobalt, the influence of orientation effects on a single crystal of cobalt was investigated. It is known that close-packed hexagonal metals with lattice dimensions giving  $c/a$  ratios of 1.633 slip in compression along the 0001 basal plane (fig. 13). If the crystal dimensions are such that the  $c/a$  ratio is less than

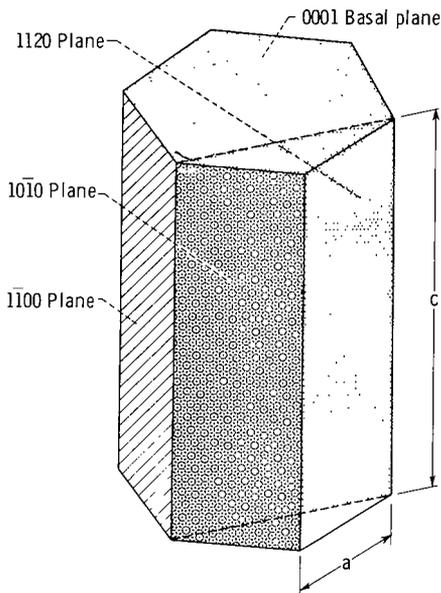


Figure 13. - Hexagonal crystal.

1.633, slip can occur along planes other than the 0001 basal plane. Friction data were obtained for two single crystals of cobalt sliding on polycrystalline cobalt. One rider specimen was oriented with the 0001 basal plane parallel to the direction of sliding and the other with the 1100 plane parallel to the direction of sliding. The deviation was  $\pm 2^\circ$  as indicated by the single-crystal supplier. The single crystals were examined at a low speed (4.5 ft/min) and at a light load (250 g) to inhibit conversion to the polycrystalline state (fig. 14(a)). When the 0001 basal plane was parallel to the direction of sliding, the final friction coefficient was lower than that obtained with the 1100 plane parallel to the direction of sliding. The initially high friction ( $>0.6$ ) for the 0001 plane oriented crystal and the initially low friction for the (1100) oriented crystal may be due to orientation deviations.

In hexagonal close-packed metals having  $c/a$  ratios of less than 1.633, the lattice is compressed along the C-axis, which tends to make the basal planes less favorable for slip inasmuch as the compression reduces the interplanar spacing. It has been experimentally demonstrated for titanium (a metal with a  $c/a$  ratio of less than 1.633) that slip occurs in the  $(11\bar{2}0)$  close-packed direction when the  $10\bar{1}0$  plane is highly stressed (refs. 22 and 23). It is stated in reference 22 that the slip planes for titanium are  $(10\bar{1}0)$  and  $(10\bar{1}1)$  and that no matter how complex the deformation in no case was slip on the 0001 basal plane.

Metals like magnesium and cobalt are, however, borderline cases with reference to modes of slip. Both metals have  $c/a$  ratios of 1.62 or very close to the normal 1.633 required for basal slip. These metals may, therefore, have one or two modes of slip. Reference 24 indicates that for magnesium basal slip occurs almost exclusively at room temperature, while at elevated temperatures both pyramidal and basal slip occur. A similar mechanism may prevail for cobalt with

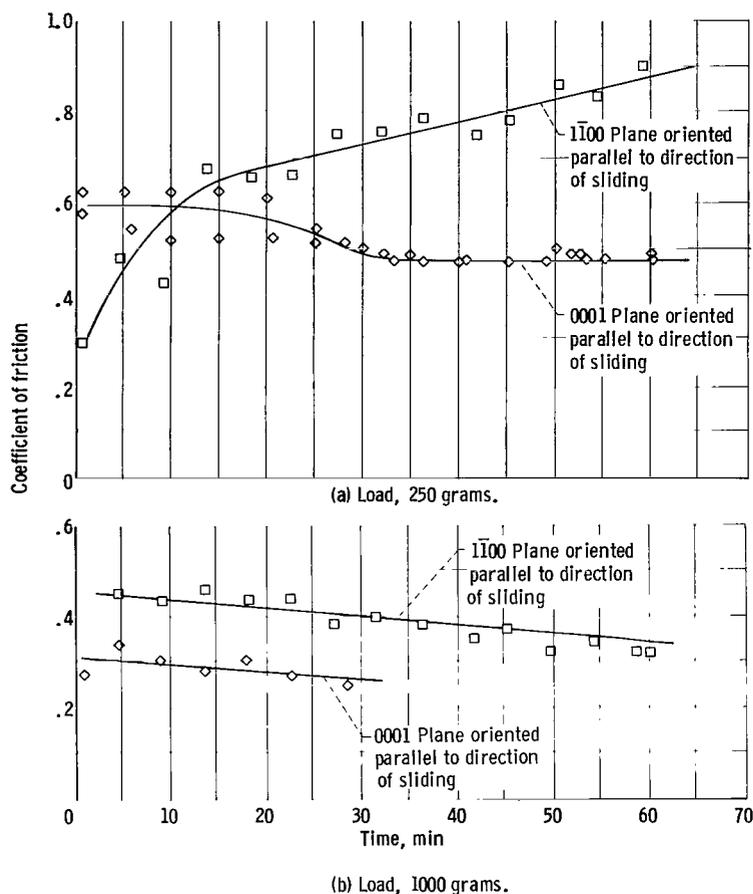


Figure 14. - Coefficient of friction for single-crystal cobalt sliding on polycrystalline cobalt in vacuum ( $10^{-9}$  mm Hg). Sliding velocity, 4.5 feet per minute; ambient temperature, 75° F.

basal slip at room temperature (ref. 25). The friction data of figure 14(a) would seem to substantiate this mechanism, since friction was lower for slip along the (0001) or basal plane in cobalt.

The load of 250 grams used in figure 14 was deliberately kept light to avoid recrystallization. The friction values obtained with the 250-gram load were higher than those obtained with polycrystalline cobalt in previous figures with a 1000-gram load. The load was therefore increased to 1000 grams, and friction data were obtained with the two single crystal orientations used in figure 14(a). The results obtained are presented in figure 14(b). With increased loads the friction coefficient decreased for both orientations; the basal slip orientation gave the lowest friction coefficient. The differences in friction between figures 14(a) and (b) are believed to be due to recrystallization

at the interface in the experiment of figure 14(b) with a polycrystalline film at the interface.

#### SUMMARY OF RESULTS

From the friction and wear data obtained in this investigation of cobalt and cobalt alloys in sliding friction experiments in vacuum, the following summary remarks can be made:

1. The crystal structure of cobalt markedly influenced its friction, wear, and metal transfer characteristics in vacuum. The hexagonal crystal form exhibited much better properties than the face-centered cubic structure.

2. Minimum friction values were obtained with hexagonal cobalt sliding on hexagonal cobalt, intermediate values with the cubic structure sliding on hexagonal, and maximum friction values with cubic cobalt sliding on cubic cobalt. Wear was also lower for the hexagonal cobalt sliding on hexagonal cobalt.

3. Differences in friction were observed for cobalt sliding on 52100 in air for the two crystal forms; the results, however, were not as marked as those observed in vacuum.

4. For single crystals of cobalt sliding on polycrystalline cobalt, a lower friction value was obtained with the single crystal oriented with the 0001 plane parallel to the direction of sliding than with the 1100 plane oriented in the same direction.

Lewis Research Center  
National Aeronautics and Space Administration  
Cleveland, Ohio, September 16, 1964

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